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EVALUATION OF COMFORT AND THERMAL EFFICIENCY IN BUILDINGS WITH PLANT SURROUNDINGS: AN EXPERIMENTAL STUDY REPORT

AVALIAÇÃO DE CONFORTO E EFICIÊNCIA TÉRMICA EM EDIFÍCIOS COM AMBIENTES DE PLANTAS: UM RELATO DE ESTUDO EXPERIMENTAL

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Abstract

With the advancement of science, mankind is increasingly understanding the relationship of climate and weather with geographic space. This provides a holistic view that enables the development of techniques that help minimize the impacts of these climatic variables on our daily lives. The present study aimed to analyze the thermal comfort of four "test cells", representing the basic standard Brazilian construction model, in view of the local climate. Each installation was subjected to different combinations of green facades and roofs and underwent temperature measurements over the course of one year. The adaptive comfort index suggested by ASHRAE was used, which establishes a methodology to determine the degrees-hours of discomfort perceived by users within a structure. The test cells with green facades and the cell with green facades and a green roof exhibited a decrease in periods of discomfort. Regarding discomfort due to cold, the green cells presented higher temperatures than the test cell without plant surroundings; when such discomfort was due to heat, they exhibited lower temperatures in most hours. These findings highlight the potential of this technique in reducing the operational costs of buildings to maintain thermal comfort. After calculating the number of cooling hours needed to obtain comfort, the test cell with green facades and a green roof required 212h (equivalent to a consumption of R$181.10), while the control

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cell, 455h (equivalent to a consumption of R$388.60), thus demonstrating the efficiency of using plant surroundings in buildings, which increase thermal comfort and reduce costs with air conditioning.

Keywords: Green facades. Green roof. Bioarchitecture. Energy consumption. Cooling.

Resumo

Com o avanço da ciência, a humanidade está cada vez mais entendendo a relação do clima e do tempo com o espaço geográfico. Isso proporciona uma visão holística que possibilita o desenvolvimento de técnicas que auxiliam a minimizar os impactos das variáveis climáticas em nosso dia a dia. O presente estudo teve como objetivo analisar o conforto térmico de quatro “células-teste”, representativas do modelo básico de construção brasileiro, tendo em vista o clima local. Cada instalação foi submetida a diferentes combinações de fachadas verdes e telhados e foi submetida a medições de temperatura ao longo de um ano. Foi calculado o índice de conforto adaptativo sugerido pela ASHRAE, que estabelece uma metodologia para determinar os graus-horas de desconforto percebido pelos usuários dentro de uma estrutura. As células de teste com fachadas verdes e a célula com fachadas verdes e telhado verde exibiram uma diminuição nos períodos de desconforto. Em relação ao desconforto com o frio, as células verdes apresentaram temperaturas mais altas que a célula teste; quando esse desconforto era devido ao calor, exibiam temperaturas mais baixas na maioria das horas. Esses achados destacam o potencial dessa técnica na redução dos custos operacionais de edifícios para manter o conforto térmico. Após calcular o número de horas de resfriamento necessárias para obter conforto, a célula de teste com fachadas verdes e telhado verde exigiu 212h (equivalente a um consumo de R$ 181,10), enquanto a célula de controle, 455h (equivalente a um consumo de R$ 388,60), demonstrando assim a eficiência do aproveitamento do entorno das plantas nas edificações, que aumenta o conforto térmico e reduz os custos com ar condicionado.

Palavras-chave: Fachadas verdes. Telhado verde. Bioarquitetura. Consumo de energia. Resfriamento.

Introduction

The past decades have been marked by extensive discussions regarding the planet’s climate and its impact on our society and economy. Understanding these complex relationships helps us plan for a future that is most likely characterized by scarcity of resources and overpopulation (FIGUEIREDO, ALVES, *et al.*, 2012). Bearing in mind that the sustainability of our actions is becoming more and more evident and necessary for the healthy maintenance of our future, humanity now finds itself in a race against time to develop technologies that assist in this journey (ALVES, LOPES, 2017).

Initially, it is necessary that we understand the relationship between climate/weather and human beings. Despite the availability of modern climate classification systems, such as Köppen (AYODE, 1996) or Monteiro (1969), when oriented towards individuals, what matters is the meteorological condition of the day in a given place, *i.e.*, the “Weather”, which, on many occasions, differs from the typical characteristics of climate classifications.

Thus emerged one of the leading areas of modern sciences known as Bioclimatology or Biometeorology, depending on the time intervals, which assesses this unique temporal relationship through various indices of thermal comfort that relate the weather conditions based on an individual’s thermal discomfort. Bioclimatology is defined as a multidisciplinary science dedicated to the study of the influence of the atmosphere on living organisms. Such influences can be thermal, barometric, hydric, luminous, or electric, and their causes can be related to ambient air composition (VECCHIA; TECH; NEVES, 2020).

With this science arose Human Bioclimatology, which explores the relationships between human health and the conditions of weather and climate. These relationships are analyzed based on meteorological data, such as global solar radiation, temperature, and relative air humidity, as well as speed and direction of prevailing winds in the area of study. Consequently, it is possible to evaluate the thermal comfort or discomfort of human beings during a given period and determine the thermal behavior of building surroundings (VECCHIA; TECH; NEVES, 2020).

Therefore, Human Bioclimatology has followed a current trend in climatology, where the central instruments comprise the variation and variability of atmospheric conditions within this adaptive science (COSTA, 2007). One of its characteristics is that, when applied to the field of architecture, it prioritizes natural strategies for acclimatization and natural lighting, allowing the reduction of project costs regarding operation and maintenance (PINTO, 2009).

The present study was developed with the objective of filling an important gap in the field of sustainability and the thermal efficiency of buildings, focusing on the pursuit of a technique that consumes the least amount of energy possible during its service life, providing maximum thermal comfort, transcending the function of a simple construction enclosure.

One way to achieve such efficiency is to regulate the energy flows of buildings, which consists of the installation of vegetation in its surroundings. Consequently, the heat losses in cold climate zones are reduced, as well as the heat gains in hot climate areas (COSTA, 2007). In addition, this method mitigates the impact of solar radiation by increasing the building's relative humidity due to plant evapotranspiration.

The use of vegetation in buildings, which ranges from a simple lawn to Patrick Blanc's sophisticated vertical hydroponic gardens (Figure 1), can be a viable alternative, offering not only indoor thermal conditioning, but also for the outdoor environment (GALLARDO, 2017). A building with plant surroundings becomes a living element within the city, increasing the green areas and generating spaces that connect ecosystems and favor urban fauna and flora.

Figure 1: Patrick Blanc's hydroponic green facade in the city of Madrid, Spain

Source: Gallardo, 2017.

These advantages are a result of the processes of evapotranspiration and photosynthesis carried out by plants. Evapotranspiration increases the humidity of the environment, which consequently assists in lowering the temperature, while photosynthesis provides the renewal of the surrounding air (ALVES, LOPES, 2017, LOPES, ALVES, *et al*., 2013) . All of these factors generate improvements in the microclimate of urban centers, especially those mostly characterized by having few green areas and high levels of pollution.

Even though vegetation is very useful in balancing the temperature, this and other elements must be used discreetly in order not to affect the lighting in the building's internal environments (COSTA, 2007).

In view of these facts, it is possible to understand that, in order to elaborate a coherent project related to bioclimatology, that contemplates efficient thermal performance and adequate esthetics, a detailed analysis of factors including openings, ventilation, lighting, and solar orientation, among others, is necessary. Thus, it is the building that requires thermal conditioning to adapt to the demands of the environment. If this is not obeyed, the use of vegetation in its surroundings can be an excellent alternative for the energy balance (MASCARÓ, 1991).

According to Dunnett and Kingsbury (2008), green facades can be used to help with the thermal performance of buildings located in both cold and hot regions. In cold climate regions they act as heat loss retardants through the building wall. In hot climates, they soften the surface temperatures of the walls through the shadow effect, in addition to generating a cooling load caused by the microclimate of the plants when they are adults.

In accordance with the new precepts of sustainable development and the breaking of controversial social paradigms, the present study aimed at analyzing the influence of different combinations of green facades and roofs on the thermal behavior of four test cells, representing a standard Brazilian construction model.

Materials and Methods

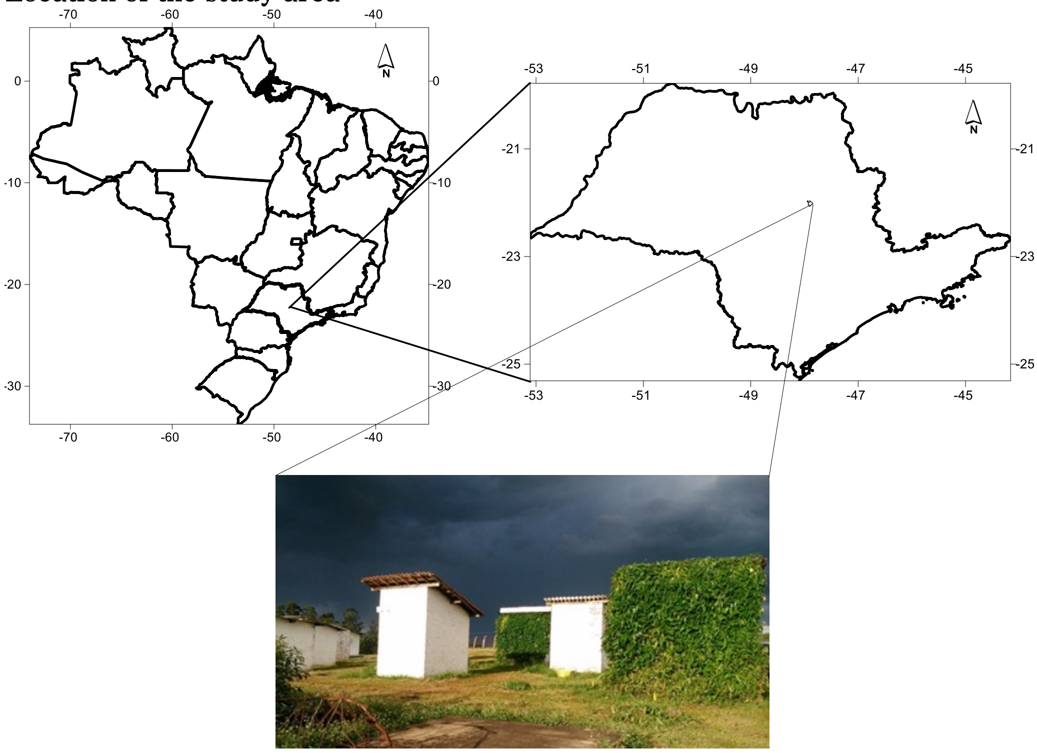
General Aspects

For the development of this study of buildings with plant surroundings, the term "test cells" was used to refer to the installations. Data regarding the Internal Surface Temperatures (IST) and the Dry Bulb Temperature (DBT) were measured using T-type thermocouples (Constantan Copper) installed in the test cells, and the climatic variables, such as radiation, air temperature, and humidity were obtained at the Weather Station of the Center for Water Resources and Environmental Studies (CRHEA) of the São Carlos School of Engineering, University of São Paulo (EESC-USP).

Location and characterization of the study area

As mentioned previously, the assessment was carried out at CRHEA (Center for Water Resources and Environmental Studies), which is located in the municipality of Itirapina, in the interior of the state of São Paulo, on the banks of the Lobo dam, at an altitude of 733 m above sea level (Figure 2).

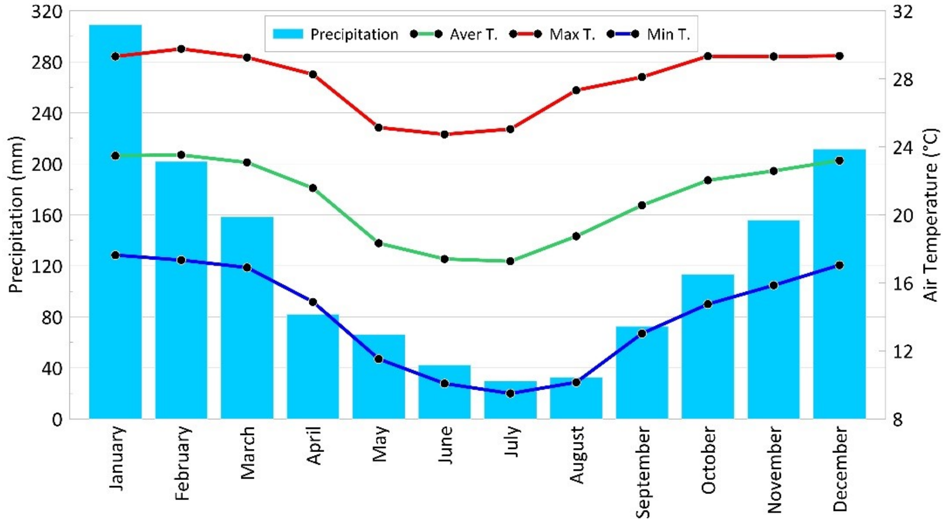
Figure 2: Location of the study area



Source: The authors.

Due to the actions of climatic genesis, the area is situated in a climate zone of complex definition on account of its location in an area of transition between polar and intertropical atmospheric systems. The region is characterized as having Tropical Highland Climate (Cwa and Cwb), according to the Köppen-Geiger climate classification, with an alternating thermal and pluviometric cold dry (April to September) and hot rainy (October to March) regime, which results in summers with higher temperatures and winters with lower temperatures, as shown in Figure 3, where it is possible to notice the temperature variation and the distribution of rainfall. The information was generated using data from the CHREA weather station.

Figure 3: Variation in temperature and rainfall distribution throughout the historical series



Source: Santos et al., 2017.

Construction system and development of the green facades and roofs

Four test cells were built with solid brick (18 x 9 x 5 cm), which were laid with cement without plaster, under a concrete sill plate (0.20 x 2.5 x 3 m). All of them were painted white, had north-facing orientation, and measured 2.2 x 2.6 x 2.9 m. Each cell had an east-facing wooden door, a north-facing wooden window, and a timber skillion roof covered with Roman-type ceramic tiles. In the cells where a green cover was installed on the roof, it was necessary to place an impermeable support slab to accommodate the plants (Figure 4).

This standardization was conducted in order for the climatic conditions to act equally and with the same intensity on each test cell. The guidelines where the green covers were planted are described in Table 1.

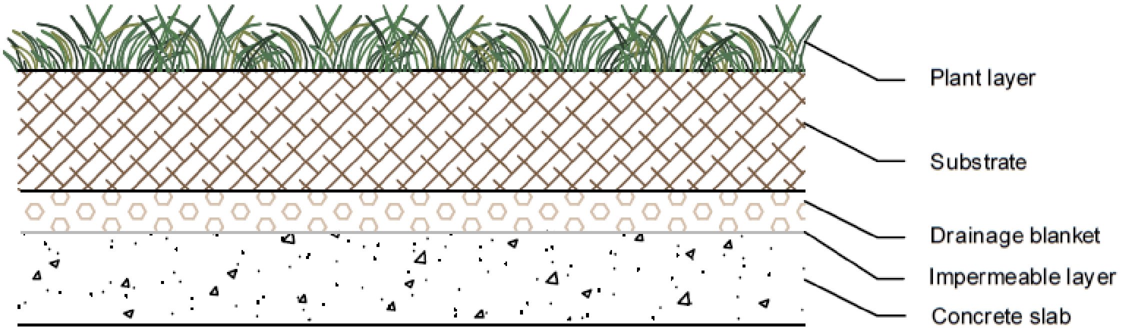
Table 1: Green cover guidelines

STRUCTURE	LOCATION OF PLANT COVERS
Control Cell (CC)	Without vegetation
Test Cell 1 (GF)	Green facades (N and W)
Test Cell 2 (GR)	Green roof
Test Cell 3 (GR+GF)	Green roof + green facades (N and W)

Source: Gallardo, 2017.

Regarding the construction of the green roofs, a pre-cast ceramic slab with prefabricated concrete beams, a slope of 23%, and 0.40-m ceramic brick slabs was built to form the cubicle where the substrate was subsequently placed. The green roof consisted of an impermeable layer, a drainage blanket, substrate extracted from CRHEA's surrounding area, and grass, as shown in Figure 4).

Figure 4: Profile of the green roof



Source: The authors.

The previously shown system consisted of the following elements:

- ***Geosynthetic blanket and drainage:*** the used drainage element was a light and flexible geosynthetic blanket, whose drainage core was formed by a three-dimensional geomembrane, composed of polypropylene filaments, with a thickness of between 10 and 18 mm, that was thermo-welded between two geotextiles with a polyester-based resin at all points of contact (VECCHIA, 2005). Two PVC pipes were placed at the lower ends for drainage.
- ***Vegetation:*** the plant chosen for the green roofs was the grass *Paspalum notatum*, which is native to the American continent and is known in Brazil as "batatais-grass", fork grass, common grass, and pasture grass (LORENZI; SOUZA, 2000). Its leaves are primarily concentrated in its basal portion. One of this plant's characteristics is its ease in covering the ground, forming large "carpets" (KISSMANN, 1997). This species is capable of adapting to poorly fertile soils, under water deficit conditions, and is resistant to the action of sunlight (GOATLEY; MALDDOX; WATKINS, 1996). The substrate and the grass were collected from the land surrounding the study site.

The vertical green system model adopted was one that did not maintain direct contact with the wall, considered one of the most low-cost methods. Its construction consisted of placing a wire mesh in a way that there was no contact with the brick facades, forming a 30º angle with the roof, as shown in Figure 5.

Figure 5: Plant growth on metallic mesh

Source: Gallardo, 2017.

The green facades were installed on the north and west sides of the test cells since they are the reference points that receive solar radiation for longer periods during the day. They consisted basically of a hexagonal 2.40-m wide by 3-m high metallic mesh, anchored to the facade and the ground using hooks (Figure 6).

Figure 6: View of a test cell with a green roof and green facades

Source: The authors.

After placing the mesh required for the upward growth of the plants, several seedlings of the species *Thumbergia grandiflora* were planted to cover the entire surface of the facades. This species belongs to the *Acanthaceae* family and is considered a low-maintenance climbing plant, originally from tropical and subtropical areas (MARTINEZ; SCOONES; PALADINI, 2002).

In order to provide the system with autonomy and ensure the maintenance and growth of the plants, both on the roofs and the facades, a sprinkler irrigation system was installed. This method, characterized as inexpensive and of maximum efficiency, consists of spraying water simulating heavy and uniform rain. In addition, it adapts to all types of soil, has an adjustable flow, and is a fully automated system, which was programmed herein to perform two irrigations per day in the dry months.

Automatic measurements

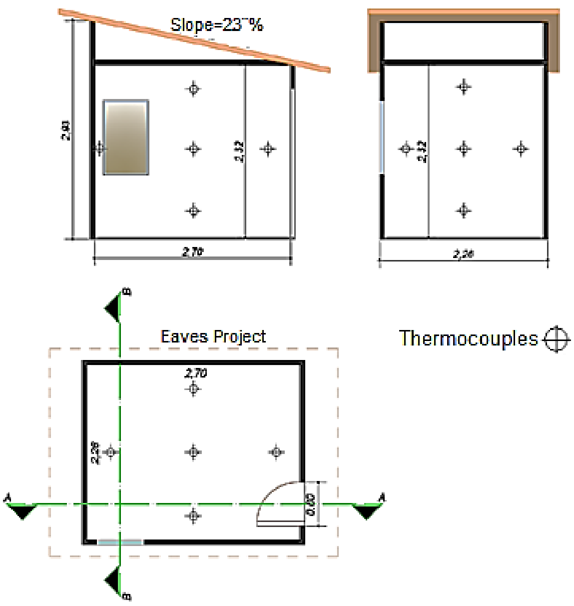
Sixteen T-type 2x24 WG thermocouples (Constantan Copper) were placed in each test cell, and their distribution is outlined in Figure 7. These instruments are considerably accurate and can measure temperature with an error of ± 0.1-0.2°C (KINZIE, 1973).

Thus, a total of 64 thermocouples were placed on the internal surfaces of the facades and ceilings, 16 in each constructive element, 15 of which measured the surface temperatures, and 1, arranged in the geometric center of each test cell, to measure the dry bulb temperature (DBT). These measurements were conducted to collect data regarding the internal surface and air temperatures to understand the thermal behavior of each test cell.

The thermocouples were connected to two 32-channel multiplexers, which, in turn, were coupled with a programmable Data Logger. The latter was connected to a battery powered by a solar panel, thus granting the equipment autonomy.

The Data Logger was programmed to record temperatures over the course of one year, with 30-second intervals and averages totaled every hour. Both devices were configured and calibrated by the manufacturing company (Campbell Scientific) before the experiments began. The distribution of thermocouples on the facades and roofs is shown in Figure 7.

Figure 7: Distribution of the thermocouples



Source: Gallardo, 2017.

Calculation of thermal comfort limits

The limits of thermal comfort were calculated as a means of theoretical support for the discussion of the results. They were estimated using the adaptive comfort index suggested by ASHRAE (2013), which establishes a method for determining the Degrees-Hours of discomfort perceived by users within a given structure.

This methodology is based on the hypothesis that people adapt to their surroundings. Its standard establishes an acceptable comfort zone based on the weighting of external temperatures on the days prior to the analyzed period. Therefore, the upper and lower comfort limits can be calculated, either for 80% or 90% of the satisfied individuals (ASHRAE, 2013).

The equations adapted for this study correspond to the comfort index for 80% of the satisfied individuals (Eq. 1 and Eq. 2).

$$\text{Upper limit 80\% satisfied} = 0.31\ t_{(pma(out))} + 21.3 \quad \text{(Eq. 1)}$$

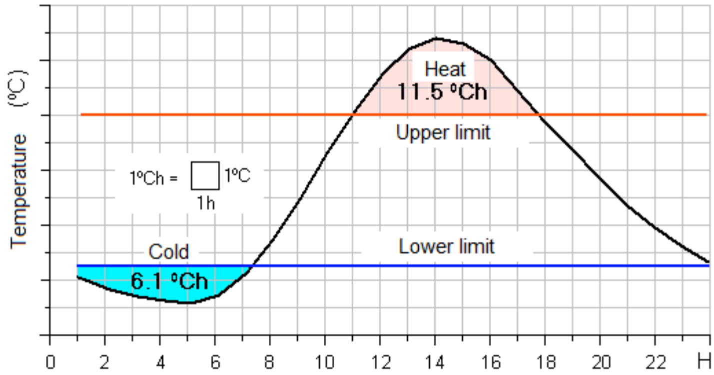
and

$$\text{Lower limit 80\% satisfied} = 0.31\ t_{(pma(out))} + 14.3 \quad \text{(Eq. 2)},$$

where $t_{(pma(out))}$ represents the average daily temperatures of the last 15 days. The comfort temperature is located at the middle of the range. Along with the thermal comfort limits, the degrees-hours of discomfort were quantified using the adaptive method recommended by ASHRAE (2013).

In order to calculate the degrees-hours of discomfort, the limit temperatures (upper and lower) and the operating temperature (DBT) for each hour are compared. The degrees-hours of discomfort are represented by the area formed below (cold) or above (heat) the curve and are generated when the internal operating temperature of the test cells exceeds the limits established by the standard, *i.e.*, positive numbers for heat and negative numbers for cold, as shown in Figure 8.

Figure 8: Comfort limits – degrees-hours of discomfort due to cold and heat



Source: Roriz, Chvatal, and Cavalcanti, 2009.

Results and Discussion

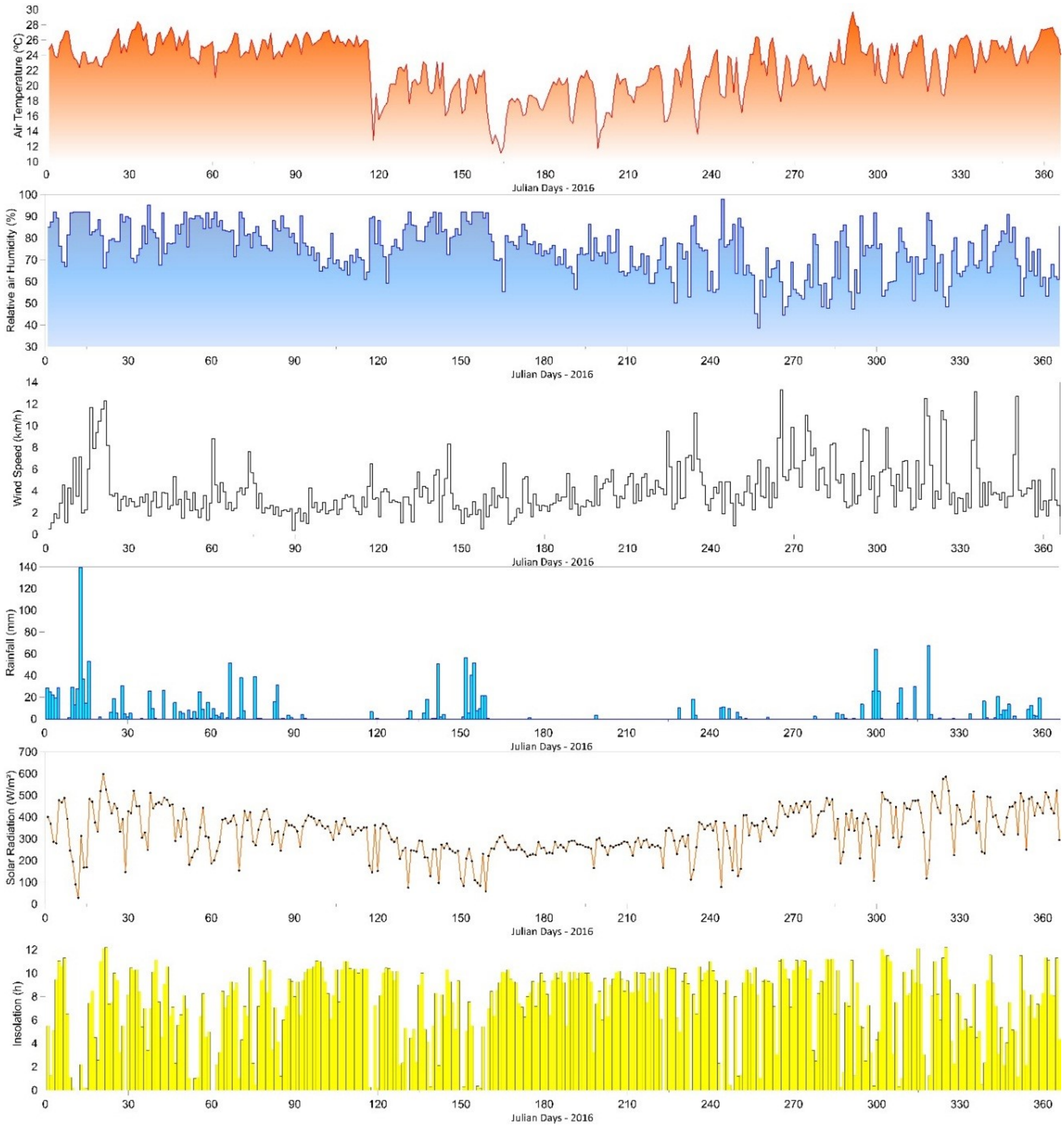
Meteorological characteristics

The temporal variability of the meteorological variables during the analyzed period, including air temperature (ºC), relative air humidity (%), wind speed (km/h), rainfall (mm), solar radiation (W/m²), and insolation (h), is shown in Figure 9. This analysis is necessary because, inside poorly ventilated buildings, the air temperatures vary, mainly, due to the gains and losses of thermal energy to the surrounding environment. Therefore, the internal air temperature is a function of the surface temperature of the elements that define the building's internal air volume. In turn, the temperature of a building's constituent elements basically varies depending on the thermal exchange that occurs with the external environment (FERNANDES *et al.*, 2015).

The air temperature in the study area showed little variation in the first four months of the year (120 days). From April to July, temperatures fluctuated significantly, with lower values than other months. Meanwhile, the relative air humidity reached a minimum between July and August, remaining above 50% in practically the entire year. Wind speed is related to the pressure difference between regions, which generates air movement, and is, therefore, directly related to the shifting of air masses on a large scale (ALVES; SILVA, 2011). The largest volumes of rain were registered from January to March, May, and from October to December.

Solar radiation and insolation are primarily influenced by cloudiness, *i.e.*, the greater the cloudiness, the lesser the solar radiation that will reach the surface, and the shorter the duration of its incidence. As a consequence, rainy periods tend to exhibit less solar radiation and insolation, as shown in Figure 9. Therefore, analyzing the internal thermal patterns in different climatic conditions is essential to understand the climate dynamics of indoor environments.

Figure 9: Meteorological characteristics during the study period



Source: The authors.

Internal air temperature of the test cells

The variation in the internal air temperature of the tested cells is shown in Figure 10, as well as the upper and lower limits of thermal comfort. It is possible to note that the limits are exceeded in some months of the year, indicating that the test cells sustained discomfort due to heat when the upper limit was exceeded and due to cold when it fell below the lower limit; when within both limits, the cell is considered thermally comfortable.

From January to February, discomfort due to heat was observed, mainly in the test cells that had only a green roof (GR) or green facades (GF) and the control (CC). The cell with a green roof and green facades (GR+GF) maintained the most constant temperatures throughout both months. Nevertheless, it is important to highlight that the hottest months of the year in the state of São Paulo are December, January, February, and March, according to data from the CRHEA-USP Meteorological Station in São Paulo.

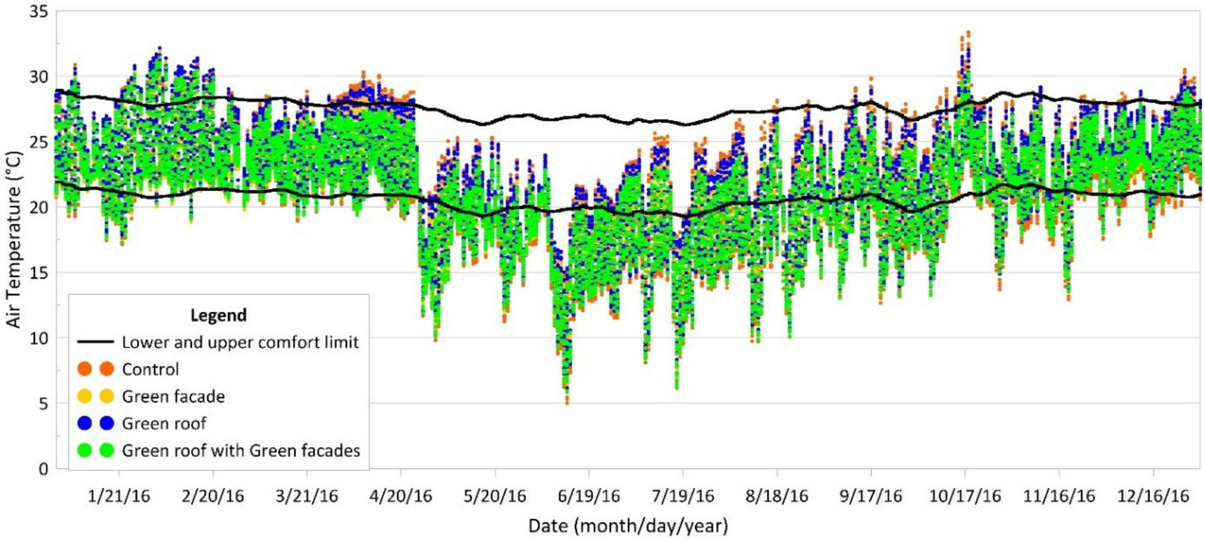
Between the months of February and March, well-balanced temperature levels were observed in all test cells. However, until the end of March, it can be noted that the GR cells exceeded the upper limit for a significant amount of time. The best performance was observed in the GR+GF cell, which maintained its internal temperature within the comfort limits throughout that period.

At the end of April and continuing until mid-October (from autumn to early spring), a significant discomfort due to cold was registered in the GF and GR+GF cells. The data in Figure 10 show that the cell temperatures almost reached 5ºC in June and July (winter season). As for the GR cells, however, even though they exhibited several variations below the lower limit, they remained the longest within the acceptable temperature range.

In the final weeks of October, the upper limit was slightly exceeded in the GR and GR+GF cells, resulting in discomfort due to heat. The temperature in the two cells reached 33ºC during that period.

From then until December (early summer, the rainiest season in São Paulo), temperature variations were observed in the four test cells, mainly with discomfort due to cold until the middle of November. Throughout December, there were also small fluctuations in discomfort due to cold and heat in those test cells, although the comfort in this period proved to be more well-balanced.

Figure 10: Internal air temperature of the test cells and the thermal comfort zone



Source: The authors.

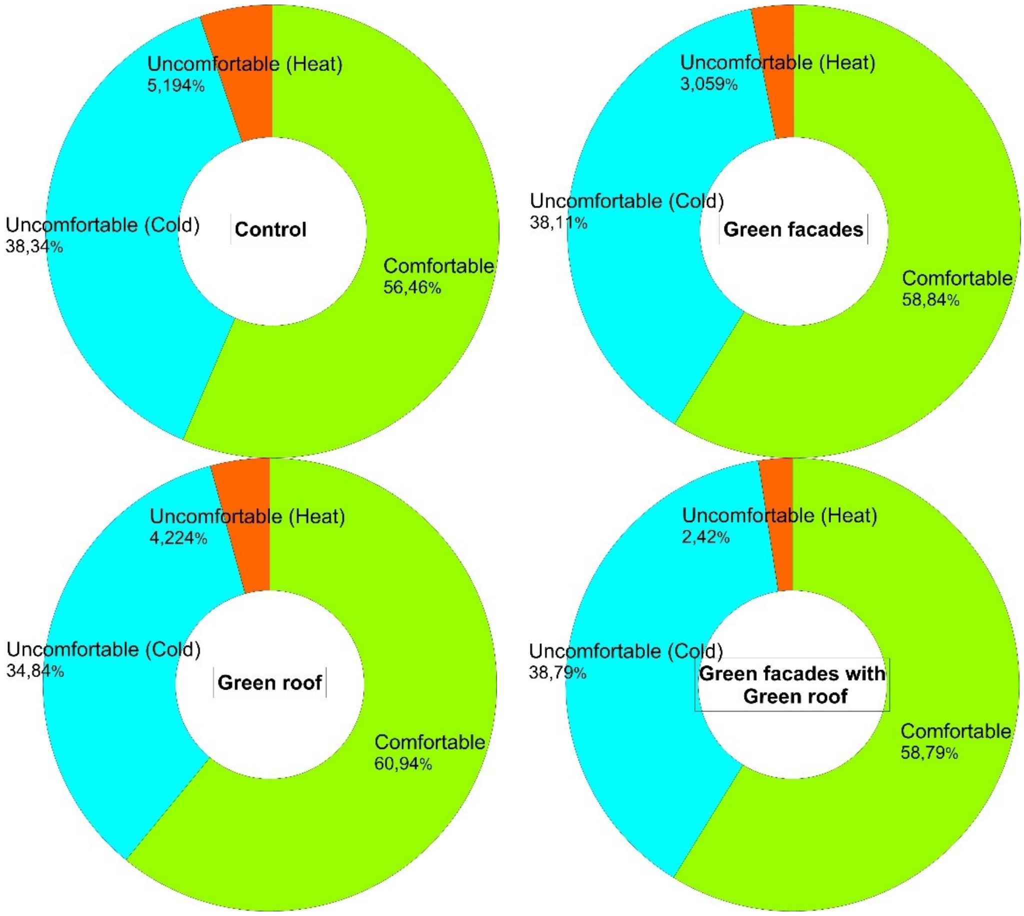
The total percentage of hours of comfort and discomfort due to cold and heat in the tested cells during the development of this study is shown in Figure 11.

In the GF cell, the hours of comfort constituted 58.84%, while discomfort due to cold was around 38.11%, and to heat, 3.059%. It is noteworthy that the discomfort due to heat in that cell was 2% less than the value reached in the Control (5.194%), which, consequently, must have generated more hours of comfort.

In the GR cell, the hours of comfort reached the highest percentage among all cells, with 60.94%. However, the graph representing that test cell shows that there was an increase in discomfort due to heat when compared to the GF cell. The results also indicate that the discomfort due to cold in the GR cell was the greatest among all cells, including the Control.

Lastly, the GR+GF cell presented superior hours of comfort when compared to the Control, although its value was lower in comparison with the cells containing only green facades or a green roof (58.79%). Nevertheless, the discomfort caused by heat generated in the GR+GF cell was the least among the analyzed cells, with only 2.42%. As for discomfort due to cold, its value can be considered intermediate (38.78%), given that it was above the lowest value (Control) and below the highest value (GR cell).

Figure 11: Hours of comfort and discomfort due to cold and to heat



Source: The authors.

According to Table 2, in periods of discomfort due to cold, the temperature in the GR, GF, and the GR+GF test cells reached higher values than those of the Control in 88.2%, 77.7%, and 67.3% of the hours, respectively. Meanwhile, in periods of discomfort due to heat, the GR, GF, and GR+GF cells reached lower temperatures than the Control in 35.8%, 11.6%, and 7.3% of the hours, respectively. Therefore, the modified test cells (GR, GF, or GR+GF) played an important role in both periods of discomfort. When it was due to cold, they exhibited higher temperatures, and when it was due to heat, their temperatures were lower in most hours.

Table 2: Percentage of hours in which the air temperature in the control cell was lower than that of the test cells in the periods of discomfort due to heat and cold.

Discomfort	Green facades	Green roof	Green facades and green roof
Cold	77.7%	88.2%	67.3%
Heat	11.6%	35.8%	7.3%

Source: The authors.

The number of monthly cooling hours that each cell would need in order to be within comfort limits is shown in Table 3, below. Fewer cooling hours in the cells indicates that they present better thermal behavior. In other words, they will require less amounts of energy to acclimatize their environments through the use of technologies aiming at temperature reduction with the use of energy sources, such as fans, central air conditioning, etc.

In January and February, the number of hours was similar in all test cells, with February being the month with the greatest need for cooling. The null values observed in the months of June, July, and August could be a result of the influence of the winter season, considered the coldest of the year, in which cooling would not be necessary due to the climate itself. Nonetheless, regarding other seasons, it is clear that the use of vegetation in the surroundings helped to provide an adequate energy balance for the cells.

The GR+GF cell showed no need for cooling over a period of eight months; in the months that it did require cooling, the number of hours was less than the other cells. In most cases, the control cell required more cooling hours than the others.

Considering the total number of hours, it can be noted in Table 3 that the GR+GF cell would need fewer cooling hours when compared to the other cells. In comparison with the control cell, there was a difference of 243 hours, a reduction of almost 50%.

The cell with the second-best result was the GF cell, which would require 268 hours of cooling. This test cell obtained very close results to the GR+GF cell, with very low values in almost all seasons. In the hottest season of the year (the summer - December, January, and February), the control cell and the GR cell exhibited the highest number of hours.

Table 3: Required number of hours of cooling to achieve thermal comfort

Months	Control	Green facades	Green roof	Green facades and green roof
January	62	56	64	48
February	119	106	124	108
March	23	9	13	0
April	93	19	63	0
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	8	0	0	0
September	22	2	9	0
October	64	36	47	30
November	10	3	5	0
December	54	37	45	26
Total	455	268	370	212

Source: The authors.

Seeing that there was a decrease in the number of cooling hours, consequently, a reduction in consumption is also achieved regarding the use of equipment to cool the environment. The costs with air conditioning for cooling the air during periods of discomfort due to heat can be seen in Table 4, in which it was concluded that the GR+GF cell would require less expenditure with air conditioning than the other test cells.

The costs were calculated based on a 1085W air conditioner's energy consumption and the rate charged by the power supply company per KW/h. Air cooling in the control cell would cost R$ 388.60 Reais annually; in the GR cell, R$ 316.00 Reais; in the GF cell, R$ 228.90 Reais; and in the GR+GF cell, only R$ 181.10 Reais, corresponding to 114.6% savings in relation to the control cell, 26.4% when compared to the GF cell, and 74.5% regarding the GR cell.

Table 4: Costs in Reais (R$) with air conditioning for thermal comfort

Months	Control	Green facades	Green roof	Green facades and green roof
January	53.0	47.8	54.7	41.0
February	101.6	90.5	105.9	92.2
March	19.6	7.7	11.1	0.0
April	79.4	16.2	53.8	0.0
May	0.0	0.0	0.0	0.0
June	0.0	0.0	0.0	0.0
July	0.0	0.0	0.0	0.0
August	6.8	0.0	0.0	0.0
September	18.8	1.7	7.7	0.0
October	54.7	30.7	40.1	25.6
November	8.5	2.6	4.3	0.0
December	46.1	31.6	38.4	22.2
Total	388.6	228.9	316.0	181.1

Source: The authors.

Final considerations

The cells constructed with green facades, a green roof, and green facades and a green roof provided longer periods of thermal comfort. The cell with green facades and the one with green facades and a green roof were efficient during most of the year, increasing thermal comfort and reducing the cost spent with air conditioning.

It is noteworthy that, as shown in the results, although a cell may provide a considerable time length of thermal balance, as observed in the case of the green roof cell, the plants responsible for causing it to cool may also end up generating greater discomfort due to cold in the rainy periods of the year. Seeing that none of the test cells produced a 100% effective system for comfort, it would be interesting to use additional devices capable of assisting in temperature regulation.

In the end, when compared to the control, the test cells proved to be an alternative to improve thermal comfort, which could induce improvements in the quality of life of people in urban environments since they evidenced the possibility of reducing costs related to expenses with cooling equipment.

The construction industry is the sector that consumes the most water, energy and generates the most waste in the world. Thus, new technologies that can incorporate the use of sustainable techniques that mitigate the environmental, social and economic impact of buildings are essential. Green roofs or green roofs, as highlighted throughout the study, help to reduce the environmental impacts of existing buildings and new buildings, and can be a great tool to be applied in cities. In addition, according to this research, it is evident that the green roof is an alternative to the environmental problems of urban centers, and that it can positively influence issues of air conditioning and rain drainage and rainwater storage.

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